SMM OBSERVATIONS OF INTERSTELLAR ^{26}Al: A STATUS REPORT

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ABSTRACT

The discovery of radioactive ^{26}Al in the interstellar medium has provided direct evidence for the recent nucleosynthesis of intermediate-mass nuclei in the Galaxy. While modern nucleosynthesis theories suggest that ^{26}Al production may occur in a variety of astrophysical objects, they have not been able to identify the dominant production site of the observed ^{26}Al. Observationally, the greatest hope for identifying its source is through a comparison of the angular distribution of the 1.809 MeV radiation, emitted during the decay of ^{26}Al, with the angular distributions of the suggested production sites. Limits on the distribution of the 1.809 MeV radiation have been obtained from data collected by the *Solar Maximum Mission* Gamma-Ray Spectrometer by using the Earth as an occulting disk in its large field-of-view. These limits are: 1) the data are inconsistent with a point source origin of 1.809 MeV radiation located at $l = 0°$, $b = 0°$ at the 4.7 σ confidence level; 2) the angular diameter for a uniform face-on disk distribution centered at $l = 0°$, $b = 0°$ is $> 10°$ at the 4.1 σ confidence level; and 3) the data are consistent with each of the diffuse distribution models studied representing ^{26}Al production by many individual events occuring throughout the Galaxy.

INTRODUCTION

The discovery of 1.809 MeV radiation from the decay of radioactive ^{26}Al in the interstellar medium (ISM) by *HEAO-3* (Mahoney *et al.* 1984), and the subsequent confirmation by *SMM* (Share *et al.* 1985*a*), represents the first direct observation of extra-solar radioactivity. These observations suggest the presence of $\sim 2-3$ $M_\odot$ of ^{26}Al in the ISM which, because ^{26}Al decays with a mean lifetime of 1.04×10^6 years, provides direct evidence that significant quantities of ^{26}Al have been synthesized in the Galaxy in the last 1 - 2 million years. An identification of the production site, or sites, of the observed ^{26}Al will provide a unique opportunity for directly comparing observation with theories of nucleosynthesis.

While nucleosynthesis was originally considered to occur primarily in supernovae (Burbidge *et al.* 1957), modern theories suggest that significant nucleosynthesis occurs in a variety

of astrophysical objects, either through hydrostatic hydrogen or helium burning during the normal phases of stellar evolution, or through explosive nucleosynthesis. Regardless of the details of the production site, however, for ^{26}Al to be observable it must be transported into the ISM from the dense, high temperature regions of its production. This suggests that the objects producing the observed ^{26}Al must be experiencing some form of mass loss, either through stellar winds or explosive events. Suggested production sites include (for an excellent review see Clayton and Leising 1987): type II supernovae (Arnett 1969) and novae (Arnould *et al.* 1980), both of which experience explosive nucleosynthesis; massive Of and Wolf-Rayet stars (Dearborn and Blake 1984) and massive pulsing red giant stars (Nørgaard 1980), all of which experience significant mass loss due to their intense stellar winds; and the explosion of a single high metallicity supermassive object ($M = 5 \times 10^5\ M_\odot$) near the Galactic Center (Hillebrandt *et al.* 1987). Currently, the best hope for identifying the dominant production site of the observed interstellar ^{26}Al is through a comparison of the angular distribution of the 1.809 MeV emission with the angular distributions of the suggested production sites. In this way, constraints may be placed on the production and ejection of ^{26}Al by the suggested sites.

To date, observations of the Galactic 1.809 MeV emission has been made by four instruments. The original satellite measurements made by *HEAO-3* and *SMM* were unable to measure the angular distribution of the 1.809 MeV radiation; however, the results of both instruments are consistent if a diffuse distribution is assumed. More recently, two balloon experiments have independently reported the detection of 1.809 MeV radiation from the direction of the Galactic Center (MacCallum *et al.* 1987; von Ballmoos *et al.* 1987). The balloon observation reported by MacCallum *et al.* (1987) favors a diffuse source at the 90% confidence level and presents a diffuse source flux which is consistent with the *HEAO-3* and *SMM* results. The results of the Compton telescope balloon observation reported by von Ballmoos *et al.* (1987), while not able to exclude the possibility of a diffuse source, appears more consistent with a point source of 1.809 MeV radiation from the direction of the Galactic Center. The goal of this work, which is presented in more detail in Purcell (1988), was to place constraints on the angular distribution of the Galactic 1.809 MeV emission.

INSTRUMENT DESCRIPTION

The *Solar Maximum Mission* (*SMM*) satellite has been in nearly continuous operation since its launch into low-earth orbit in February of 1980. One of seven instruments on the *SMM* spacecraft, the Gamma-Ray Spectrometer (GRS) was designed to provide both line and continuum studies of the Sun in the energy range 0.3 – 9.0 MeV (Forrest *et al.* 1980). The primary detecting element of the GRS consists of a set of seven high resolution 3-inch diameter × 3-inch thick NaI(Tl) scintillation crystals, providing an on-axis effective area of 79 cm^2 at 1.8 MeV. During the production processing, the data from these detectors are accumulated into 65 second intervals and recorded. A 1-inch thick CsI(Na) annular shield and 3-inch thick CsI(Na) back plate define a field-of-view of 160° FWHM at 1.8 MeV. Plastic scintillation detectors covering the front and back of the detector provide anticoincidence for charged particles and complete the $4\text{-}\pi$ anticoincidence shielding. Active gain stabilization of the primary detectors has allowed the comparison of data collected over long periods of time. It is precisely the excellent stability of the GRS instrument and the long data set available which allows the study of celestial sources of gamma-radiation using the GRS.

The GRS axis has remained oriented toward the Sun throughout most of its mission. Since the Sun passes near the Galactic Center in late December, the Galactic Center region is visible for ~ 3 months each year as it passes through the large GRS field-of-view. It was the presence of an annual modulation of the 1.809 MeV line flux which led to the original *SMM* detection of ^{26}Al; however, significant constraints could not be placed on its angular distribution. It is the combined use of Earth occultation, the large GRS field-of-view, and the over eight years of nearly continuous data which makes a detailed study of the distribution of the 1.809 MeV radiation possible.

^{26}Al DISTRIBUTION MODELS

Since the GRS is not an imaging instrument, it can not directly measure the angular distribution of the 1.809 MeV emission. Rather, an angular distribution model must be assumed and then compared with the data, so the angular distributions representative of the suggested production sites must be identified. For this work, two scenarios for the production of the observed interstellar ^{26}Al have been explored: 1) the ^{26}Al is assumed to be the result of nucleosynthesis by many individual events occurring throughout the Galaxy, and 2) the ^{26}Al is assumed to be the result of nucleosynthesis in a single event taking place in the direction of the Galactic Center.

If the observed ^{26}Al was produced by many individual events occurring throughout the Galaxy, its distribution would then be expected to follow the Galactic distribution of its production site. The suggested production sites can be separated into two Galactic populations: 1) Population I objects, including type II supernovae, Of and Wolf-Rayet stars, and massive ($M \gtrsim 3$ M$_\odot$) red giants; and 2) Population II objects, of which novae are members. Figure 1 shows two longitude distribution models for each of these Galactic populations. These models have been normalized to the 1.809 MeV flux of 0.033 photons sec^{-1} reported by Share *et al.* (1985*b*). The distribution models for Population I objects are based on observations of interstellar carbon monoxide (CO) and are labeled CO Model #1 and CO Model #2. CO Model #1, from Leising and Clayton (1985), is based on a model for the radial distribution of molecular clouds in the Galaxy while CO Model #2, from Dame *et al.* (1987), represents the observed CO flux integrated along the line of sight and in Galactic latitude within $\pm 1.25°$. The distribution models for Population II objects are based on observations of novae in M31 and are labeled Nova Model #1 and Nova Model #2. Nova Model #1, also from Leising and Clayton (1985), is based on a model for the radial distribution of nova in M31 while Nova Model #2, from Mahoney *et al.* (1985), is based on the assumption that the distribution of Galactic novae follows the visual luminosity.

If the observed ^{26}Al was produced by a single event, its distribution would be expected to follow roughly that of a face-on disk centered on the production site. The angular size of the disk would depend on the distance and age of the event. Two models were selected to examine this case; the Point Source Model and the Disk Model. The Point Source Model represents a point source of 1.809 MeV radiation while the Disk Model represents a uniform, face-on disk distribution having an angular diameter of ~ 10°. From von Ballmoos *et al.* (1987), the centroid of the 1.809 MeV emission was found to be consistent with the Galactic Center, so the centroids of these models were located at $l = 0°$, $b = 0°$. These models were also normalized to the 1.809 MeV flux reported by Share *et al.* (1985*b*).

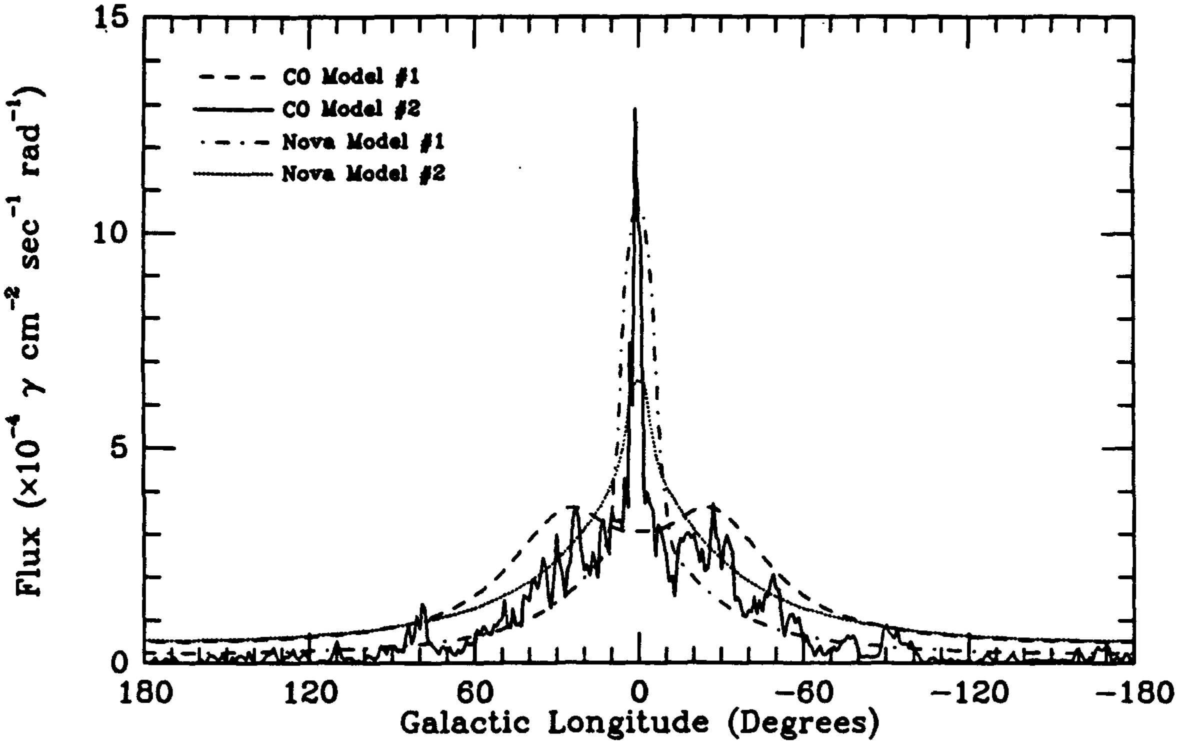

Figure 1: The ^{26}Al Galactic longitude models used in this work, normalized to the 1.809 MeV flux reported by Share *et al.* (1985*b*).

ANALYSIS TECHNIQUE

Using the Earth as an occulting disk in the intrinsically large GRS field-of-view, a technique of data selection has been developed which significantly improves the GRS angular resolution. This method, which can be applied to nearly any celestial position, also significantly reduces the instrumental background features produced by isotopes having half-lives $\gtrsim$ 10's of minutes. The data selection method consists of identifying spectra as either source or background measurements based on whether a selected celestial position was occulted by the Earth during the spectral accumulation. If the celestial position was occulted, the associated spectrum is considered to be a background measurement, otherwise the spectrum is considered a source measurement. Using this technique, data were selected to perform observations of celestial positions at five degree intervals along the Galactic plane within $\pm 70°$ of both the Galactic Center and the Galactic Anti-center; the Galactic Anti-center positions were used to monitor any residual systematic effects. In order to optimize the signal-to-noise, the following data selection criteria were applied. First, the data were required to have been collected > 10,000 seconds after the last significant passage of the *SMM* satellite through the South Atlantic Anomaly. Second, all data collected during known transient events were excluded. Third, only data collected when the GRS field-of-view was within 40° of the Galactic Plane were used. Finally, for the observation of each celestial position, the source spectra were defined as those collected when the celestial position was between 1° and 13° above the horizon, while the background spectra were defined as those collected when the celestial position was between 1° and 13° below the horizon. Only occultation transitions for which there were both source and background measurements available were used. In order to fur-

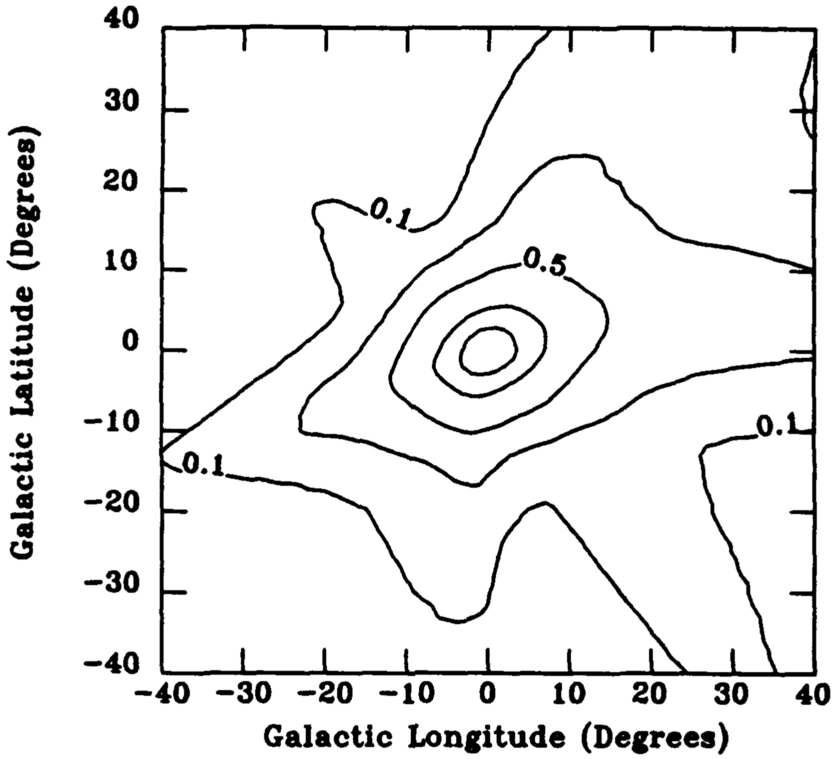

Figure 2: The normalized effective field-of-view for the Galactic Center observation. The contour levels are at 10, 25, 50, 75, and 90% of the peak response.

ther reduce the systematic effects, the source minus background differences were performed for each occultation transition separately, and the resulting background subtracted spectra accumulated for all of the valid occultation transitions. The same procedure was followed for each celestial position.

Once the spectra had been selected and the differences performed for the observation of each celestial position, the effective GRS field-of-view was generated for each observation by estimating the sky exposure for each of the individual spectra used. The effective field-of-view for the observation of the Galactic Center is shown in Figure 2. The asymmetry seen in this figure, which is found to vary with celestial position, is attributed to the orbital geometry and to periods during which the GRS instrument was placed into an in-flight calibration mode during which no data are available.

RESULTS AND CONCLUSIONS

The final difference spectrum for the observation of each celestial position was fitted over the range 1.5 – 2.1 MeV by a model consisting of three gaussian lines, one at 1.809 MeV and two background lines, and a continuum term. The lines were fixed in energy and in width at the instrument resolution (95 keV at 1.8 MeV). Analysis of the resulting 1.809 MeV fluxes indicated the presence of a residual systematic effect at the $\lesssim 1 \times 10^{-4}$ counts cm^{-2} sec^{-1} level. This systematic was attributed to a prompt ($\lesssim$ 1 second) background line at 1.809 MeV produced by neutron interactions on ^{27}Al. It was found that this residual

Table 1:

Results of Statistical Analysis

	Reduced χ^2	
^{26}Al Distribution Model	Galactic Center	Galactic Anti-center
Point Source	2.71 ($2x10^{-4}$%)	0.80 (77%)
Disk Source	2.40 ($4x10^{-3}$%)	0.84 (71%)
CO Model #1	1.24 (17%)	1.06 (38%)
CO Model #2	1.14 (28%)	0.90 (62%)
Nova Model #1	1.38 (8%)	1.01 (45%)
Nova Model #2	1.14 (28%)	1.13 (29%)

systematic effect could be reduced below the statistical level by using the magnetic L-shell parameter as a measure of the cosmic-ray environment of the spacecraft during the spectral accumulations. The results of the spectral fits for each of the celestial positions, with the systematic effect removed, are shown in Figure 3. This figure also shows the expected signal for each of the ^{26}Al distribution models discussed above. As can be seen from the data in the Galactic Anti-center direction, most of the residual systematic effects have been eliminated. Since the final difference spectra for any two celestial positions may have used some of the same individual spectra, they are not statistically independent. A Monte Carlo simulation was used to estimate the covariance between adjacent positions; the errors shown in Figure 3 have been corrected for this covariance term.

A χ^2 test was applied between the data and each of the distribution models. The resulting reduced χ^2, for 29 degrees-of-freedom, and the corresponding probability for each distribution model is given in Table 1. Included in Table 1 are the results of the analysis of the Galactic Anti-center observations to demonstrate the validity of the analysis method. The results of the statistical analysis are that: 1) the data are inconsistent, at the 4.7 σ confidence level, with a point source origin of 1.809 MeV radiation located at the Galactic Center, 2) the angular diameter of diffuse emission (uniform face-on disk) centered on the Galactic Center is $> 10°$ at the 4.1 σ confidence level, and 3) the data are consistent with each of the CO and nova angular distribution models studied.

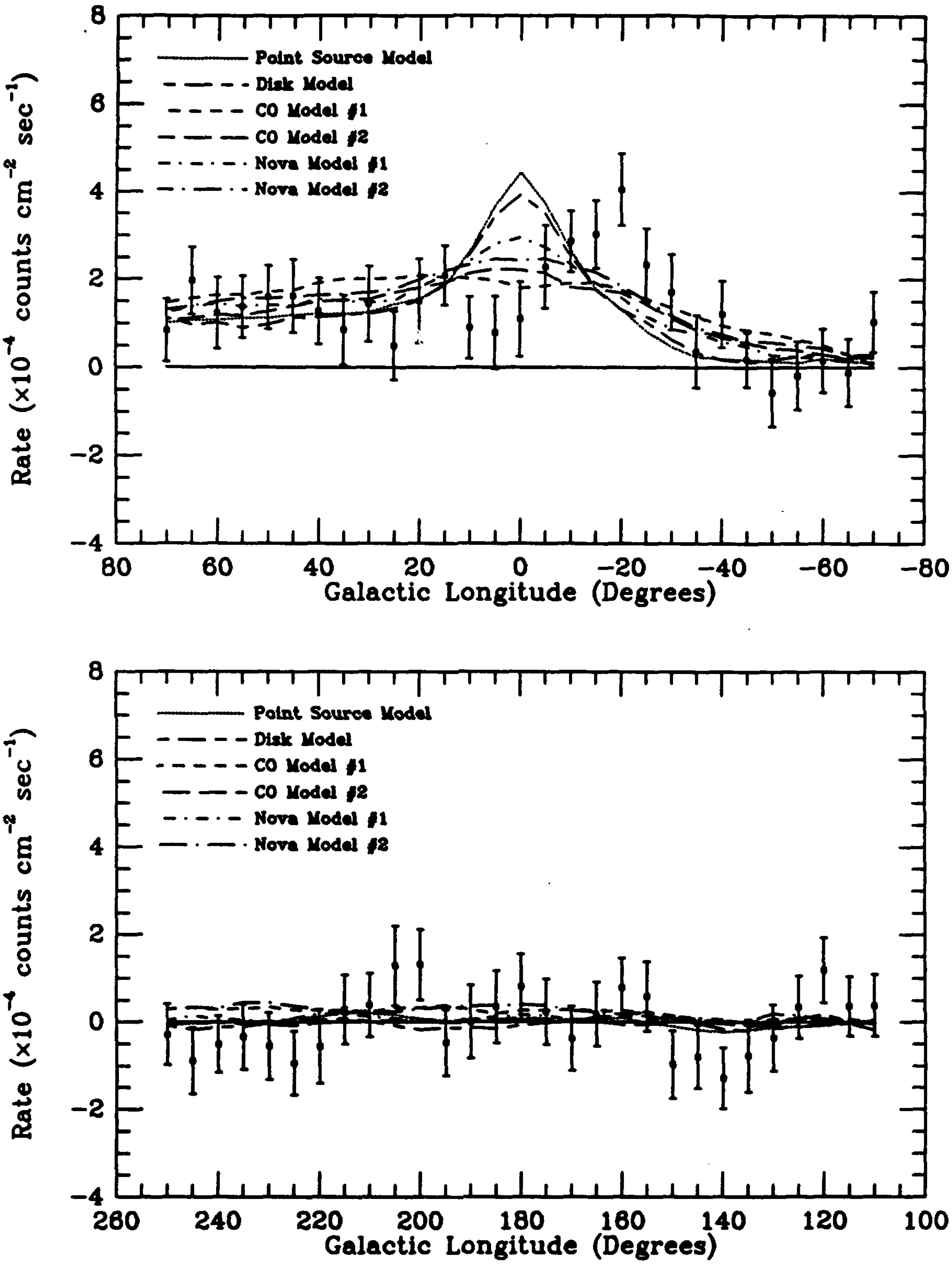

Figure 3: The background corrected counting rates for observations of positions in the direction of the Galactic Center (*upper*) and the Galactic Anti-center (*lower*). Note that this does *not* represent the *distribution* of the 1.809 MeV radiation. Also shown are the expected responses for each of the ^{26}Al distribution models.

The GRS observation of the Galactic Center using this technique, for which the effective field-of-view was $\sim 22°$ FWHM (see Figure 2), is found to be $(1.1 \pm 1.0) \times 10^{-4}$ photons cm^{-2} sec^{-1}. This value is consistent with the fluxes of $(1.4 \pm 0.9) \times 10^{-4}$ and $(1.3 \pm 0.9) \times 10^{-4}$ photons cm^{-2} sec^{-1} reported by Mahoney *et al.* (1986) and MacCallum *et al.* (1987), respectively, and is $\sim 1.9\ \sigma$ below the flux of $(6.4 \pm 2.6) \times 10^{-4}$ photons cm^{-2} sec^{-1} reported by von Ballmoos *et al.* (1987). The $\sim 2.3\ \sigma$ excess seen in Figure 3 for the observation of the $-20°$ longitude position would seem to suggest the presence of a concentrated source of 1.809 MeV emission in this direction. Due to the statistics available, however, and since the data are well fitted by the diffuse models, no significant conclusions about this excess can be made at this time. Work is in progress to study positions out of the Galactic plane in an attempt to place constraints on the latitude extent of the 1.809 MeV emission.

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